PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 :
C03B 37/014, 37/018

A1

(11) International Publication Number: WO 99/32413

(43) International Publication Date: 1 July 1999 (01.07.99)

(21) International Application Number: PCT/US98/27418

(22) International Filing Date: 23 December 1998 (23.12.98)

(30) Priority Data:
08/997,308 23 December 1997 (23.12.97) US

(71) Applicant: SPECTRAN CORPORATION [US/US]; 50 Hall Road, Sturbridge, MA 01566 (US).

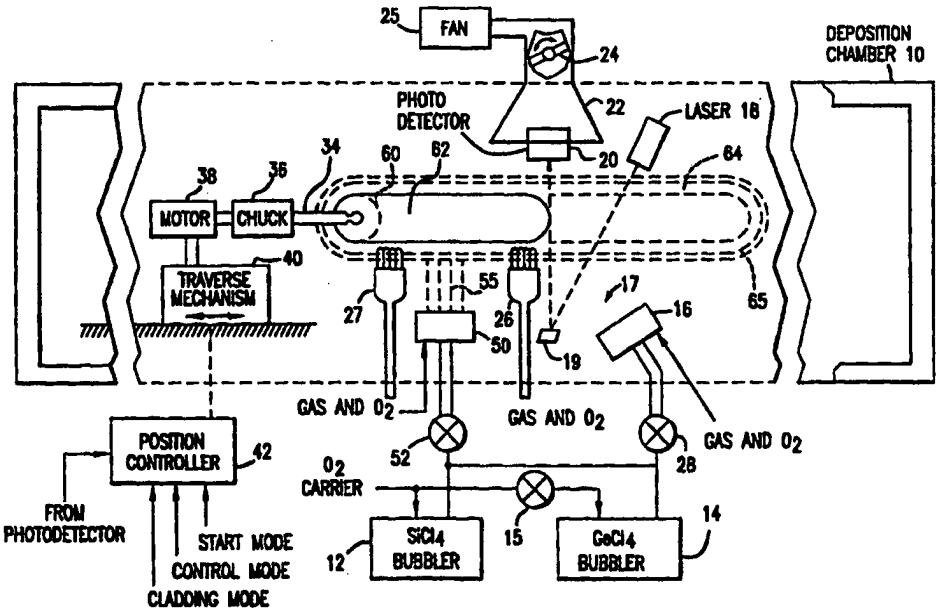
(72) Inventors: WU, Fengqing; Apartment 208, 295 Turnpike Road, Westboro, MA 01581 (US). HUERTA, Aurelia; 200 Main Street, Sturbridge, MA 01566 (US).

(74) Agents: MILLER, Charles, E. et al.; Pennie & Edmonds LLP, 1155 Avenue of the Americas, New York, NY 10036 (US).

(81) Designated States: CN, KR, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: METHOD OF MAKING LARGE SCALE OPTICAL FIBER PREFORMS WITH IMPROVED PROPERTIES



(57) Abstract

Core soot material (62) is deposited via a stream (55) onto a target (34). At least one additional layer (64) is deposited on the core material (62). A cladding layer (65) is deposited on the previous layer (64). Then this item is dehydrated, sintered and formed into a plurality of fibers.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	**ES**	Spain	**LS**	Lesotho	**SI**	Slovenia
AM	Armenia	**FI**	Finland	**LT**	Lithuania	**SK**	Slovakia
AT	Austria	**FR**	France	**LU**	Luxembourg	**SN**	Senegal
AU	Australia	**GA**	Gabon	**LV**	Latvia	**SZ**	Swaziland
AZ	Azerbaijan	**GB**	United Kingdom	**MC**	Monaco	**TD**	Chad
BA	Bosnia and Herzegovina	**GE**	Georgia	**MD**	Republic of Moldova	**TG**	Togo
BB	Barbados	**GH**	Ghana	**MG**	Madagascar	**TJ**	Tajikistan
BE	Belgium	**GN**	Guinea	**MK**	The former Yugoslav Republic of Macedonia	**TM**	Turkmenistan
BF	Burkina Faso	**GR**	Greece			**TR**	Turkey
BG	Bulgaria	**HU**	Hungary	**ML**	Mali	**TT**	Trinidad and Tobago
BJ	Benin	**IE**	Ireland	**MN**	Mongolia	**UA**	Ukraine
BR	Brazil	**IL**	Israel	**MR**	Mauritania	**UG**	Uganda
BY	Belarus	**IS**	Iceland	**MW**	Malawi	**US**	United States of America
CA	Canada	**IT**	Italy	**MX**	Mexico	**UZ**	Uzbekistan
CF	Central African Republic	**JP**	Japan	**NE**	Niger	**VN**	Viet Nam
CG	Congo	**KE**	Kenya	**NL**	Netherlands	**YU**	Yugoslavia
CH	Switzerland	**KG**	Kyrgyzstan	**NO**	Norway	**ZW**	Zimbabwe
CI	Côte d'Ivoire	**KP**	Democratic People's Republic of Korea	**NZ**	New Zealand		
CM	Cameroon			**PL**	Poland		
CN	China	**KR**	Republic of Korea	**PT**	Portugal		
CU	Cuba	**KZ**	Kazakstan	**RO**	Romania		
CZ	Czech Republic	**LC**	Saint Lucia	**RU**	Russian Federation		
DE	Germany	**LI**	Liechtenstein	**SD**	Sudan		
DK	Denmark	**LK**	Sri Lanka	**SE**	Sweden		
EE	Estonia	**LR**	Liberia	**SG**	Singapore		

METHOD OF MAKING LARGE SCALE OPTICAL FIBER PREFORMS WITH IMPROVED PROPERTIES

Table of contents

I. FIELD OF THE INVENTION

This invention relates to improved methods of making optical waveguides and optical waveguide preforms and products by vapor deposition techniques.

II. BACKGROUND OF THE INVENTION

The most commonly used techniques for optical waveguide manufacture are based on dissociation in a flame of glass forming constituents to build up a porous preform of vitreous particles called "soot." The "soot" preform is converted to a glassy state by sintering at an elevated temperature. The final product is drawn from a combination

of core and cladding layers drawn under given temperature and tension conditions.

An early, widely used optical waveguide manufacturing process is the "inside vapor deposition," process, also known as the modified chemical vapor deposition process (MCVD). In the MCVD process a soot core is deposited within the interior of a hollow, silica tube. After vitrification, the core-tube body is compacted prior to or during the drawing of a preform. A plasma chemical vapor deposition (PCVD) process similarly employs a hollow silica tube to deposit glass soot material within the tube. Disadvantages of the MCVD and PCVD processes include that silica tubes are costly, and further that the size of the preform that can be made is restricted.

Another widely used alternative is the outside vapor deposition (OVD) process. The OVD process is referred to as "radial" deposition because soot material is deposited radially around a pre-existing, rod shaped mandrel. Once deposition is complete, the mandrel is removed from the deposited material prior to further processing into a preform. The removal of the mandrel is a delicate procedure and therefore imposes a length restriction on the resulting preform.

In about 1977 a vapor-phase axial deposition (VAD) process was devised for continuous soot deposition and preform manufacture. This process is described, for example, in Vol. 1, page 97 et seq., of the book, "Optical Fiber Communications, edited by Tingye Li, and published (1985) by the Academic Press, Inc.

In a VAD process, a glass soot stream is directed toward the central vertical axis of a rotating deposition target. Relative axial movement is provided between the soot stream and the target, as soot material is axially deposited and grown into a cylindrical core. The VAD process overcomes disadvantages associated with the use of mandrels and tubes in the above methods.

The cylindrical core resulting from a VAD process can be continuously sintered, if desired, to provide a glass start rod. Alternatively, additional soot cladding layers can be concurrently deposited over the surface of the cylindrical core with a separate soot stream directed radially toward the axially developed core. The diameter of the glass start rod, therefore, may be readily increased, unlike the case with MCVD or PCVD processes.

The limitations of the VAD process, however, have become more apparent, as the usage of optical waveguides has increased, and the technical requirements by communication systems have become more demanding. Currently, signal attenuation of 0.4 dB per kilometer, low dispersion, and precise cut-off wavelength characteristics are often sought. These requirements dictate that optical waveguides have, in addition to very low impurities and a homogeneous microbubble-free structure, a reliable and predictable refractive index profile. In addition to tighter technical specifications, production costs and yields for making glass preforms must be satisfactory for mass production quantities. As a result, VAD processes used heretofore are now less than satisfactory from one or more standpoints.

A number of practical limitations limit the effectiveness of the VAD approach to realizing the goals of inexpensive manufacture, greater yields, and tighter optical specifications. For example, when concurrent radial deposition is used to build up a cladding layer, it is difficult to synchronize the rates of radial and axial buildups without introducing unwanted core diameter variations. Additionally, when two separate soot streams operate simultaneously in the same chamber, there is inevitable mixing of soot streams resulting in an undesirable, diffuse interface between the core and the cladding.

Some of these disadvantages are overcome using the redeposition or "hybrid" (HVD) process for making preforms. The HVD process, as discussed in U.S. Pat. No. 5,028,246,

uses as a first step an axial VAD torch to deposit a soot core using a high velocity laminar soot stream at an angle greater than 60° relative to the axis of the core cylinder. Then, as a subsequent step, a pure silica cladding is deposited with an OVD soot stream. One key difference between VAD and HVD processes is the tilt angle formed between the deposition torch and the core axis. The tilt angle for the VAD method is less than 60°, whereas the HVD process uses a tilt angle which is larger than 60°.

The HVD process, however, may not provide the larger preform and reproducibility necessary for mass scale production of high quality optical fibers. Moreover, much process control is required to obtain uniformity of the refractive index profile along the preform because of the tendency for soot core tapering and high frequency diameter variation along the core length. One method to meet the cutoff wavelength and mode field diameter specifications is to cut a core rod into two or three pieces. The variation in the zero dispersion wavelength is often inadequate for many applications because of inconsistencies in the refractive index profile. As a result, the original HVD process was not widely practiced in the fiber optics industry.

The interested reader is directed for additional background material to the following references.

J. B. MacChesney, P. B. O'Connor, F. V. DiMarcello, J. R. Simpson, and P. D. Lazay, "Preparation of Low-Loss Optical Fibers Using Simultaneous Vapor-Phase Deposition and Fusion," pp. 40-45 in Proceedings of Tenth International Congress on Glass (Kyoto, Japan), Vol. 6, Ceramics Society, Japan, 1974.

T. Edahiro and N. Inafaki, "Materials and processes for Fiber Preform Fabrication-Vapor Phase Final Deposition," Proc., IEEE, 68[10] pp. 184-87 (1980).

D. B. Deck, P.C. Schultz, and F. Zimar, "Method of Forming Optical Waveguide Fiber," U.S. pat. no. 3,737,292 (1973).

D. Koppers and H. Lydtin, "Preparation of Optical Waveguides with the Aid of Plasma-Activated Chemical Vapor

Deposition at Low Pressures", pp 108-30 in Topics in Current Chemistry, Vol. 89, Springe-Verlag, Berlin, 1980.

Arnab Sarkar, U.S. Pat. Nos 5,028,246; 5,364,430, and 5,558,693.

F. Wu, A. Huerta, and R. Sumner, "HVD Single-Mode Core Rod Process Status and Development Program, Spectran Technical Report, November 1995.

T. Moriyama, O. Fukuda, K. Sanada and K. Inada, "Ultimately low OH content VAD optical fibers," Electronics Lett., 16, p. 698 (1980).

A. Love, S. Middelman, and A. K. Hochberg, "The Dynamics of Bubblers as Vapor Delivery Systems," J. of Crystal Growth 129, pp. 119-133 (1993).

R. J. Betsch, J. Crystal Growth 77, p. 210 (1986).

K. Sanada, T. Moriyama, and K. Inada, "Chlorination and vaporization of GeO_2 Component in SiO_2:GeO_2 porous Preforms in Dehydration Process by VAD Method and Spontaneous Formation of SiO_2 Cladding Layer during the Dehydration by Selective vaporization of GeO_2," J Non-Cryst Solids, 194, pp. 163-172 (1996).

N. Niizeki, N. Inagaki and T. Edahiro, "Vapor-Phase Axial Deposition Method," Optical Fiber Communications Vol. 1, Fiber Fabrication, Edited by Tingye Li, Academic Press, p. 158 (1985).

Tingye Li, "Fiber Fabrication," in Optical Fiber Communication, Vol. 1, p. 97-. Academic Press, Inc. 1985.

As a result of these and other disadvantages associated with current technologies, it is perceived that there is a need for an improved manufacturing method for providing large scale optical fiber preforms with improved optical properties.

III. SUMMARY OF THE INVENTION

In accordance with the present invention, the soot on soot on soot (SSS) method of making preform involves the

following basic steps. First, a soot core is axially deposited with a soot stream provided by an axial torch. This soot core cylinder then acts as a mandrel for further soot deposition, which becomes integrated with the final core. Second, additional soot core material is deposited on the core cylinder using a radial deposition method. Thus, the completed soot core comprises the axial soot core and the additional soot core layers deposited in the second step. In accordance with the present invention, the resulting soot core cylinder from this second step is both large and uniform in diameter unlike cylinders that are made using prior art methods. Third, in a preferred embodiment, a small amount of silica soot cladding is deposited. The soot boule is next purified and sintered to a glass core rod. This core rod is then stretched down to obtain a smaller diameter for further cladding. Any further cladding necessary for a proper b/a ratio, where b is the cladding radius, and a is the core radius, can be added either by providing additional soot cladding layer(s) or using a rod-in-tube, over-jacketing method.

More specifically, in accordance with the present invention a method of making a preform for optical waveguide fibers having low attenuation is disclosed comprising the steps of: depositing a core soot material along the axis of a rotating target by directing a first stream of core soot material towards the rotating target to develop a first soot core having predetermined length and substantially uniform density or a predetermined density profile; and depositing one or more additional layers of core soot material over the first soot core using a second stream of core soot material positioned radially at an angle substantially perpendicular to the axis of rotation.

In accordance with another aspect of the present invention, a method of making optical waveguide fibers having very low attenuation is disclosed comprising the steps of: depositing a core soot material along the axis of a rotating target by directing a first stream of core soot material

towards the rotating target to develop a first soot core having predetermined length and substantially uniform density or a predetermined density profile; depositing one or more additional layers of core soot material over the first soot core using a second stream of core soot material positioned radially at an angle substantially perpendicular to the axis of rotation, developing a substantially uniform density soot core cylinder having a substantially uniform diameter along its length; depositing cladding soot material on the outer surface of the soot core cylinder with a radial stream of cladding soot material to provide a cladding layer coextensive with the soot core cylinder; drying and sintering the product thus formed; and drawing the dried and sintered product into optical waveguide fibers.

The present invention eliminates the need for synchronization of radial deposition with axial deposition and provides a low hydroxyl ion and void-free soot-soot interface. The soot core boule obtained in accordance with the present invention has a substantially uniform diameter and a refractive index uniform along its length, because the radial deposition layering of the final soot core used in accordance with the present invention reduces tapering and periodic diameter variations of the axially deposited first soot core. In accordance with the present invention soot core preforms require no mandrels and can be made with high repeatability, at high deposition rate.

Significant and unexpected results were achieved in practical implementations of the process in accordance with the preferred embodiment of the invention. In particular, deposition of additional core material by axial and subsequent radial deposition has led to the production of single-mode fibers per core preform with at least a 300 percent yield increase over the previous axial deposition techniques of the prior art.

IV. BRIEF DESCRIPTION OF DRAWINGS

A better understanding of the invention may be had by reference to the following description, taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a combined, simplified perspective and block diagram view of a system in accordance with the invention for fabricating optical waveguide cores and preforms;

FIG. 2 is an enlarged side view of a torch and soot stream configuration used in core deposition.

FIG. 3 is a block diagram of steps in a method of forming one type of optical waveguide in accordance with the present invention.

FIG. 4 is a flow chart of steps for an SSS single-mode fiber manufacturing method in accordance with a specific embodiment of the present invention.

FIG. 5 is a typical refractive index profile of an SSS core rod for making single mode fiber.

FIG. 6 is a histogram of cutoff wavelengths in 1500 km SSS single-mode fibers.

FIG. 7 is a histogram of mode field diameter in SSS single-mode fibers.

FIG. 8 is a scatter plot of measured cutoff wavelengths along fiber length from the SSS core rod Z2019 with same cladding thickness.

FIG. 9 is a bar plot of OTDR measured attenuation at 1310 nm on fibers made by SSS process.

FIG. 10 is a bar plot of OTDR measured attenuation at 1550 nm on fibers made by SSS process.

FIG. 11 is a histogram of attenuation at 1385 nm in SSS single-mode fibers.

FIG. 12 is a histogram of zero dispersion wavelength of SSS single-mode fibers.

FIG. 13 is a histogram of dispersion slope data of SSS single-mode fibers.

FIG. 14 is a scatter plot of the relationship between zero dispersion wavelength and the product of mode field diameter and cutoff wavelength.

FIG. 15 is a scatter plot of dependence of dispersion slope on zero dispersion wavelength in SSS single-mode fibers.

FIG. 16 is a histogram of cladding non-circularity of SSS single-mode fibers with tube over-jacketing.

FIG. 17 is a histogram of core non-circularity of SSS single-mode fibers with tube over-jacketing.

FIG. 18 is a histogram of core/clad offset of SSS single mode fibers with tube over-jacketing.

V. DETAILED DESCRIPTION OF THE INVENTION

A. System Description

Fig. 1 shows in block diagram form a system for practicing the method of the present invention. The system generally comprises an axial traverse mechanism 40, a deposition chamber 10, a radial cladding torch 50, an axial core torch 16, end burners 27, 26, a chemical delivery system 12, 14 and a control unit 42.

In a preferred embodiment, the operative components of the system are mounted within a large enclosed deposition chamber 10. A first bubbler 12, which may be inside or outside the chamber 10, contains purified precursor materials, such as a silica compound like $SiCl_4$. Silica glass precursor vapors are forced out of the first bubbler 12 by directing a carrier gas, preferably oxygen or other suitable media, under pressure into the bubbler 12. A second bubbler 14 contains purified precursor dopant materials, which in a preferred embodiment is a germania compound $GeCl_4$. Dopant precursor vapors are forced out of the second bubbler 14 by the O_2 carrier. A valve 15 in the O_2 carrier line can be operated to shut off the second bubbler 14, when desired. The entrained glass forming compounds in the vapor stream are

mixed and are dissociated, upon being fed into a first torch 16 held, in the illustrative embodiment shown in FIG. 1 in substantially fixed position relative to the deposition zone.

The axial torch 16 generates a streamlined soot stream 17 that is directed toward the bait rod 34 upwardly, at an angle preferably greater than about 60° relative to the rotation axis of the bait rod 34. A narrow light beam from a laser 18 is directed off a mirror 19 and onto a photodetector 20. The beam of the mirror 19 is angled to intercept the axis at the geometric center of the deposited material. The soot stream 17 is, however, not centered on the geometric center but is offset both radially and axially by predetermined amounts, as known in the art.

Within the deposition chamber 10 a relatively short length of silica bait rod 34 is centered along the reference axis on a chuck 36. In a preferred embodiment, the chuck 36 and bait rod 34 are rotated at a selected rate, preferably about 28 r.p.m., for core deposition, by a rotary drive 38 mounted on a linear traverse mechanism 40. A position controller 42 receiving signals from the photodetector 20 in the core deposition mode can run the traverse mechanism 40 unidirectionally, and at a desired rate. The traverse mechanism 40 can be made to reciprocate through any chosen length of travel at a desired rate by bypassing the position controller 42. In the core deposition mode the bait rod 34 is first reciprocated through a short distance, and thereafter moved unidirectionally under position control. The traverse mechanism 40 can also reciprocate through a substantial total length for deposition of subsequent soot core layers and cladding.

A side, or radial, torch 50 within the deposition chamber 10 is spaced along the reference axis from the bait rod 34 and separately used for radially depositing additional soot core layers and, subsequently, cladding layers. In depositing additional soot core layers, the radial torch 50 is fed from the first bubbler 12 and the second bubbler 14, when valve 52 is open, with a particulate forming compound,

preferably a mixture of pure $SiCl_4$, $GeCl_4$, and O_2 carrier gas. Other forming compounds can be used, as known in the art.

The chemical components in the soot stream 17 emanate at a velocity of preferably about 40 ft/sec. In a preferred embodiment, other gases flow out at velocities of about 25 ft/sec. Other velocities can be used in alternative embodiments, if necessary. An exhaust outtake 22 immediately above the target area collects gases and non-impinging particulates at a gas flow rate of approximately 300 ft/min. A first end burner 26 adjacent the axial torch 16 aids in bringing the temperature at the point of deposition up to a given level before deposition begins. A valve 28 can be turned on or off to control usage of the axial torch 16.

The system used in a preferred embodiment of the present invention is described, for example, in U.S. Pat. Nos. 5,028,246; 5,364,430, and 5,558,693 the content of which is hereby incorporated for all purposes. Other systems may also be used in accordance with the principles of the present invention.

B. The SSS Process

(1) Axial Core Deposition

Formation of a first soot core for an optical waveguide preform is accomplished in a preferred embodiment using an axial deposition. In accordance with the present invention, the deposition chamber 10 is first cleaned, and the bait rod 34 is mounted in the chuck 36, and centered on the axis of rotation. The axial torch 16 is positioned with respect to the laser beam that defines the tip of the deposited material during position control. The axial torch 16 is then lit, the exhaust velocity is maintained, and conditions are allowed to stabilize before the bait rod 34 is rotated, preferably at about 28 r.p.m., by the drive 38, and advanced into the path of the first soot stream 17 containing core particulates. The soot stream 17 impinges on and about the leading end of the bait rod 34, which is oscillated back and forth preferably at a rate of about 45 cm/hr. A bulbous starter tip 60 develops over the free end of the bait rod 34, to a length of approximately 2 cm. When sufficient material has been deposited, in accordance with the present invention, this bulbous tip 60 forms an adequate base or anchor for development of a first soot core 62.

Axial development of the first soot core 62 commences, in accordance with the preferred embodiment, with the position controller 42 initially providing a fixed withdrawal rate of about 12 cm/hr. The first soot stream 17 sprays the end of the bulbous starter tip 60, initializing the first soot core 62. With the chemical constituents of the soot stream at a velocity of preferably about 40 ft/sec and the other gases having a velocity of preferably about 25 ft/sec, the flow in the stream 17 used in accordance with the present invention is laminar, and the deposition rate is approximately 0.14 grams per minute. The high flow rate in an upward direction is accompanied by some overspray, but gases that bypass the first soot core 62 are exhausted in the system shown in FIG. 1 through the outtake 22. As deposition

of the first soot core 62 begins, the withdrawal rate of 12 cm/hr is slightly faster than the first soot core 62 growth rate, but enables growth to be equilibrated on the bulbous starter tip 60. The position controller 42 is then switched to the servo mode, with the laser beam intercepting the geometric center of the free end of the first soot core 62. The position controller 42 responds to the signals from the photodetector 20 by withdrawing the core cylinder 62 so as to maintain its free end in a constant position as matter is deposited. This establishes a non-constant withdrawal rate of between 6 and 8 cm/hr, to give a first soot core 62 about 2.5 cm in diameter.

In a preferred embodiment, the first soot core 62 continues to grow and is withdrawn by the traverse mechanism 40 until a total length in excess of about 20 cm (usually in the 20-30 cm range) is achieved.

(2) Soot Deposition for Subsequent Core Layer(s)

In accordance with the present invention, the next step is to form one or more additional soot core layers onto the first soot core 62. To this end, when the desired length of the first axially grown soot core 62 has been attained, the torch 16 is turned off. The first soot core is withdrawn back to the left side of the end burner 27 to wait for subsequent deposition. The radial torch 50 and the two end burners, 26 and 27, are then turned on and allowed to stabilize. The traverse mechanism 40 is controlled to move back and forth so that the first soot core 62 will be in the path of the chemical stream 55 emitted from radial torch 50. With the first soot core being rotated at a selected speed, e.g., 28 rpm, a soot layer will be deposited on the surface of the first soot core 62 as it passes through the chemical stream 55. The two end burners 26 and 27 are used to pre-densify the previously deposited soot core layers before the next soot layer is applied by the side torch 50. Soot core layers are added using radial deposition until a selected

diameter is achieved resulting in a final soot core cylinder 64.

While not depicted in Figure 1, in accordance with alternative embodiments of the present invention, multiple soot streams may be simultaneously employed for forming additional soot core layers onto the first soot core 62 by placing another radial torch displaced at an angle or in such manner as to avoid soot stream interference. The use of multiple radial torches to increase deposition speed is also applicable to the radial cladding process discussed next.

(3) Cladding Deposition

In accordance with the method of the present invention, the next step is the cladding deposition. With the desired length and diameter of the soot core cylinder 64 developed, the radial torch 50 is now supplied with a suitable cladding agent, as known in the art, and allowed to stabilize. The traverse mechanism 40 is actuated to reciprocate the length of the core cylinder 64 in opposition to the side torch 50. With the core cylinder 64 turned at about 20 r.p.m. in a specific embodiment by the rotary drive 38, the radial torch 50 is held at a substantially constant distance from the axis of rotation of the soot core cylinder 64. The soot core cylinder 64 is then traversed back and forth relative to the cladding chemical stream 55 by the traverse mechanism 40 at a rate of about 250 cm/hr.

In a preferred embodiment, cladding deposition of a pure silica soot particulate takes place at an average rate of approximately 2.5 grams per minute derived by flame hydrolysis of the carrier borne vapor from the first bubbler 12. The deposition temperature at the surface of the soot core cylinder 64 is gradually raised to a normal operating level by incrementally increasing the gas/oxygen flow rates over the first fifteen minutes of operation, until a thin contact layer of approximately 5 mm has been deposited on the soot core cylinder 64. The resultant lower temperatures avoid boil-off of germania (GeO_2) from within the soot core

cylinder 64, but the initially deposited cladding particulate nonetheless firmly unites to the surface of the core soot cylinder 64. Thus, in accordance with the present invention, the interface between the soot core cylinder 64 and a fully developed outside cladding layer 65 is in the nature of a very thin transitional layer of substantially constant characteristics and very low moisture content, factors which are of substantial significance to the refractive index profile and hydroxyl ion content of the ultimate optical waveguide.

Deposition of cladding layer 65 is continued until a final diameter is obtained, giving a ratio of cladding radius (b) to core radius (a) of preferably about 2:1 or greater. Lower ratios are possible in alternative embodiments. As cladding is added, the surface velocity increases, although the rate of increase slows as the radius becomes larger. The burner temperature is increased in steps with time to correspond generally to surface velocity, so as to maintain density substantially constant. Additional aspects of this process are discussed, for example, in U.S. Pat. Nos. 5,028,246; 5,364,430 and 5,558,693 which are incorporated by reference.

Drying and sintering is performed after all soot core layers and partial cladding are deposited.

(4) Core Preform Rod Draw and Final Cladding

In accordance with the method of the present invention, in a second cladding step, the preliminary glass preform rods are cladded with a soot process or an over-jacketing process to proper thickness before fiber draw. In the soot cladding process, the glass preform rods are again rotated and reciprocated across the soot stream from radial torch 50, to deposit a further cladding soot layer of the desired thickness on the drawn rod. When built up to a suitable diameter, the redeposited rod is then dried and sintered as before to provide a final fiber preform. Such

preforms are themselves commercial products because many manufacturers prefer to draw their own optical waveguides.

To form an optical waveguide, the preform rods are drawn, in conventional fashion, to a final fiber diameter of 125 μm for operation at 1310 to 1550 nm wavelength. These optical waveguide fibers, with silica-germania cores and silica cladding, are single mode fibers having a b/a ratio of about 13, and attenuation typically about 0.33 dB/km, at 1310 nm and more typically 0.2 dB/km, at 1550 nm and dispersion of less than 3.5 ps/nm/km in the wavelength range between 1280-1330 nm.

It will be appreciated that a number of alternatives can be employed at different stages in the process. For example, the angle between the core soot stream and the rotation axis of the core can be kept the same, but the reference axis can be tilted relative to the horizontal, and the soot stream directed more nearly vertical, or purely vertical, with the exhaust outtake being reconfigured if needed to provide clearance about the core cylinder while providing the function of extracting overspray. The vitrified rods can be cleaned in a variety of ways, including dry gas etching and high intensity laser beam polishing as well as fire polishing.

In another embodiment of the present invention, a further step of separately depositing additional cladding layers over the soot core using radial, multiple-pass deposition is performed. The final soot core with a chosen cladding thickness is then dried, sintered, and drawn to form optical waveguide fibers.

In yet another embodiment in accordance with the invention, the cladding may be fluorinated during zone sintering to lower the refractive index below that of a pure silica core.

In yet another embodiment in accordance with the invention, the deposition of core soot and cladding soot materials may be conducted while the soot core axis of rotation is positioned vertically rather than horizontally.

While extended horizontally, the maximum deposition length is limited by the weight of the soot core and its ability to support itself.

In yet another embodiment of the invention, the position and flow of the soot streams may be varied to make waveguides that have specific refractive index profiles.

In yet another embodiment of the invention, the deposition of additional layers of soot core material may be conducted by a plurality of soot streams simultaneously.

In yet another embodiment in accordance with the invention, the cladding soot stream is of substantially uniform cross-section. The cladding soot stream velocity directed at the soot core may be increased during deposition so as to limit surface temperature until an initial cladding layer is built up on the soot core cylinder.

Referring to FIG. 2, the first torch 16 used for core deposition is shown, along with the relative geometries of the gas streams. The chemical soot stream 17 emanates from a central aperture 70 around which an inner ring of orifices 72 provides an inner shield of oxygen flow. An intermediate ring of flammable gas and oxygen orifices 74 provides a circular flame that converges slightly. A final outer shield of oxygen emanates from orifices 76 in an outer ring. This arrangement maintains the chemical soot stream with a substantially constant diameter which provides the needed flame for disassociation.

Referring now to FIG. 3, it shows one embodiment of the method in accordance with this invention, where optical waveguides of even lower attenuation (i.e., about 0.2 dB/km or less) are provided by using a pure silica core and a cladding of a lower index of refraction. In the first two steps, a pure silica soot core is deposited and additional soot core layers are deposited, as depicted in FIG. 1. This body is then dried and sintered, and a cladding, also of silica soot, is deposited thereon to a desired thickness. This soot layer is then dried at about 1150°C. in a hydrophilic atmosphere. Subsequently, it is zone sintered in

a fluorinating atmosphere (using SF_6) to permeate the soot with a desired fluorine content concurrently with consolidation. Subsequently, another layer of silica soot may be added, and thereafter dried and sintered to provide the desired total cladding thickness.

The drying and sintering steps are carried out in a closed furnace into which gas flows are injected at controlled rates as the body is held at a controlled temperature. In a preferred embodiment for drying, the furnace is heated to a temperature in the range of 800-1250°C over 20 minutes with a chlorine flow of 350 cc/min, helium flow of 7000 cc/min and oxygen flow of 140 cc/min, then held for 30 minutes at 1150°C under the same conditions. After this time, the preform is withdrawn with the same flows maintained, the withdrawal being effected within 10 minutes.

With the HVD method, pure silica soot cladding was directly deposited on the axial soot core. In contrast, the SSS method used in accordance with the present invention deposits more core material along with the axial core before the deposition of silica soot cladding. This modification provides at least the advantages listed below.

An advantage of the present invention is that a large sized initial core rod decreases the relative diffused interface thickness between the core and the cladding in the final fibers, which improves the fibers' bending sensitivity.

Another advantage of the present invention is that the resulting large soot core cylinder makes large scale production of high quality optical fibers feasible. As illustration, the process described in the Example below, yields over 360 km single-mode fibers per core preform compared to 120 km using a single step, axial deposition process. Thus, more core deposited with radial deposition increases process productivity by over 300 percent. Further increases in fiber output can be easily achieved by depositing more GeO_2 doped silica layers with the radial torch.

As yet another advantage of the invention, the combination of the axially deposited first soot core and the radially deposited additional soot core layers can provide another dimension to control the refractive index profile, so as to enable making, for example, step-index profiles, triangular profile and semi-parabolic profiles, by adjusting the position of the axial torch 16 and varying chemical flows to the radial torch 50.

Yet another advantage of the method of the present invention is that an axially deposited soot cylinder could have some diameter variations caused by an unstable chemical delivery system, such as bubbler temperature fluctuation and carrier gas flow fluctuation. The core cylinder diameter variation will result in mode field diameter variations in the resulting fibers. In preforms made in accordance with the present invention, however, because a significant part of total core material is deposited layer by layer radially, the diameter variations of the axially formed first soot core are reduced in the final soot core cylinder. Therefore, the effect of an unstable chemical delivery system on soot deposition is reduced to a very low level; repeatability of the process is increased, rendering the method of this invention much more suitable and practical for large scale, high quality optical fiber manufacturing.

The large core rod size and excellent optical characteristics provided by the present invention makes it possible to produce one core rod that yields up to a thousand kilometers of a single-mode fiber. This presents a significant commercial advantage in large scale optical fiber production.

Following is a description of a specific example illustrating the advantages of the improved manufacturing method in accordance with the present invention.

VI. EXAMPLE

A. Experiment Description

This example is a typical process for making silica based low loss single mode-fiber using the method of the present invention. FIG. 4 shows a flow chart of the partial OVD process for SSS single-mode fiber manufacturing. Following is a summary of the basic steps in producing the core soot boule.

1. Axial deposition of the first soot core was performed using an axial torch. $SiCl_4$ and $GeCl_4$ flow rates during deposition are 119.4 and 44.5 cc/min respectively. The deposition temperature is maintained at 1150°C by an optical pyrometer aimed at the geometrical center of the soot core deposition.

Typical chemical flow rates used at different deposition steps are shown in Table 1.

	$SiCl_4$ carrier O_2	$GeCl_4$ carrier O_2	CH_4	Total O_2	Deposition T
	cc/min	cc/min	cc/min	cc/min	°C
1st soot core (step 1)	119.4	44.5	~1200	~2600	1150
2nd soot core (step 2)	410-450	371-420	3000-3500	5000-5700	-
Soot cladding (step 3)	474-700	0	3400-3900	4300-6200	-

Table 1. Chemical flows used at different deposition steps in SSS mini production at P_{atm} = 750mmHg.

	He	Cl_2	O_2
	cc/min	cc/min	cc/min
Pre-drying period	7000	0	400
Dehydration period	7000	480	0
Consolidation period	9000	65	0

Table 2. Chemical flow rates for drying and sintering.

Pressure compensation was used to stabilize chemical delivery. Bubbler temperature settings for $SiCl_4$ and $GeCl_4$ were set at 51°C and 55°C respectively. Table 2 shows chemical flows used for drying and sintering.

2. Radial deposition of additional soot core layers was applied with multiple passes of soot stream using a radial torch. The initial $SiCl_4$ and $GeGl_4$ deposition flow rates are 410 and 371 cc/min, respectively. As more layers are deposited, the $SiCl_4$ and $GeCl_4$ deposition flow rates are increased to 450 and 420 cc/min, respectively, at the final layer. A total of 18 soot layers is deposited.

3. Radial deposition of a cladding layer with multiple pass using the same radial torch, followed by drying, sintering and rod draw. Only pure silica is deposited to create the cladding layer. The initial $SiCl_4$ deposition flow rate is 474 cc/min, which is gradually ramped up to 700 cc/min, layer by layer. A total of 44 pure silica soot layers are applied.

4. After a first rod draw, additional cladding is deposited to bring the b/a ratio to between about 3 to about 5.6., followed by drying, sintering and rod draw.

In this example, after the second rod draw in step 4, the rods with the partial cladding were radially deposited with additional soot layers or over-jacketed with 1400 mm^2 CSA synthetic silica glass tube and then drawn to a final fiber.

B. Results

Using the modified SSS method in accordance with the present invention for single-mode fiber manufacturing, ten consecutive core rods were made. Each core rod yielded three 120km single-mode preforms. A total of 29 core preforms were obtained with the partial OVD process and either tube over-jacketing method or a complete soot process. The related process parameters are listed in Table 3.

	Clad diameter (mm)	Core diameter (mm)	b/a ratio	Length (cm)
Soot core preform	130	45	2.89	33
Sintered core rod	64	22.55	2.84	11
1st row draw dia.	23.6	8.30	2.84	55
Partial OVD soot cladding	100	8.30	-	55
Core rod with partial OVD cladding	48	8.30	5.4	50
2nd rod draw diameter	17.4	3.22	5.4	270
Finished SM preform	45.7	3.22	14.2	3x90

Table 3: Process dimension parameters with partial OVD cladding/tube jacketing method.

The example SSS single-mode fiber waveguide structure is a matched-cladding design. A typical refractive index profile is shown in FIG. 5. Because functional properties, such as cutoff wavelength and mode field diameter, are mainly determined by fiber refractive index profiles, variations of cutoff wavelengths and mode field diameters were used to evaluate the process stability and capability for single-mode fiber manufacturing. The targeted parameters for this single-mode waveguide structure are listed in Table 4. FIGS. 6 and 7 show histograms of both cutoff wavelength and mode field diameters from 1500 km, SSS single-mode fibers. Cutoff wavelength variation is mainly caused by core diameter variations. A tighter cutoff wavelength has been achieved with all-soot cladding process to provide even more precise cladding thickness. Overall, more than ninety percent of the fibers produced met cutoff wavelength and mode field diameter specifications targeted in Table 4.

Historically, HVD core rods have had significant core diameter variations, which consists of both core rod

diameter tapering and periodic variation along the core. The core diameter taper is caused by soot cylinder sagging during deposition. The periodic diameter variation along the core is mainly caused by chemical bubbler temperature fluctuation. With the SSS process in accordance with the present invention, more than half of the core materials is axially deposited. The multiple-pass deposition method overcomes, to some degree, high frequency variation in the core diameter caused by unstable deposition. Therefore, the overall axial uniformity of a soot core deposited both axially and radially is improved over that produced solely by an axial, core torch. FIG. 8 shows the measured cutoff wavelengths along 250 km single-mode fibers from one SSS core rod with the same cladding thickness. All measured cutoff wavelengths are near 1250 nm with some degree of variation along the core rod. However, there is no significant cutoff wavelength variation along the core rod, which is critical for large scale fiber manufacturing.

(1) Attenuation

Fiber attenuation is low in the fibers made by SSS technique. Results show that fiber attenuation is peaked at 0.33dB/km at 1310 nm and 0.185dB/km at 1550 nm, respectively. FIGS. 9 and 10 show OTDR measured attenuation at both 1310 nm and 1550 nm in 2100 km SSS single-mode fibers compared with MCVD fibers. The results also show that more than 90 percent of SSS fibers have attenuation equal to or less than 0.34dB/km at 1310nm and 0.2dB/km at 1550 nm respectively.

Hydroxyl content in SSS fibers was low. As shown in FIG. 11, most fibers displayed attenuation of 0.5 db/km at 1380 nm. This means, OH concentration in most SSS fibers was less than 5 ppb, if the relation between loss increase at 1380 nm and OH content is 65 dB/km/ppm. Such low OH content is achieved by a good drying/sintering process and by removing "wet" glass surface on a core rod before radial cladding is applied.

(2) Dispersion Properties

Zero dispersion wavelength and dispersion slope were measured for all fibers produced in SSS pilot production. Average zero dispersion wavelength was 1316 nm, with a standard deviation of 2.63 nm. Average dispersion slope was 0.0851 ps/nm^2-km, with a standard deviation of 0.0025. Histograms of dispersion properties are shown in FIGS. 10 and 11. The relationship between measured zero dispersion wavelength and product of mode field diameter and cutoff wavelength is shown in FIG. 14.

Because material dispersion in standard single-mode fibers does not vary much from fiber to fiber, any variation in fiber zero dispersion or dispersion slope comes mainly from the variation of refractive index profile and core diameter. Any deviation from the step type reactive index profile may cause unwanted changes in the fiber's dispersion properties. With the present example, the center zero dispersion wavelength stays at 1314 nm, with a cutoff wavelength and mode field diameter of 1270 nm and 9.4 μm, respectively, as seen in FIG. 12. With the method in accordance with the present invention, the refractive index profile can be manipulated with varying chemical flows layer by layer during the radial deposition step. Therefore, it is possible to precisely change the zero dispersion wavelength by modifying the refractive index profile in SSS single-mode fibers. However, because SSS fibers have matched cladding with diffused interface between core and cladding, the optimal design parameters may not exactly coincide with other fiber designs, such as those with a depressed barrier layer made by an MCVD method.

(3) Geometric Properties

Typical geometric properties of fibers made with tube over-jacketing were observed in the present SSS fibers. As shown in Fig. 16, cladding non-circularity varies in value from 0.1 to 1.2 percent, with a peak near 0.5 percent. Core non-circularity depends mainly on the core making process

itself. As shown in FIG. 17, 99 percent of fibers in accordance with the present invention have non-circularity of less than 5 percent, with most fibers having non-circularity of less than one percent. Core/clad offset is determined mainly by the over-jacketing process. FIG. 18 shows a core/clad offset histogram of SSS fibers. About five percent of SSS fibers have offsets more than one micrometer.

The overall performance of the SSS single-mode fibers manufactured in the pilot production is listed in Table 4. Table 4 shows that most of the fibers lost are due to core/clad offset (6.43%) and cutoff wavelength (8%). This loss has been dramatically reduced when an all-soot cladding process is used to make SSS single-mode fibers. With all-soot cladding, exact cladding thickness can be made to meet precise cutoff wavelength specifications. The core and cladding concentricity can also be improved when the target rod is well aligned during radial soot deposition.

Standard single-mode fibers made with the SSS process have shown excellent performance. More than ninety percent of fibers have attenuation of less than 0.34dB/km at 1310 mn and 0.2 dB/km at 1550 nm.

While there have been described above and illustrated in the drawings various forms and modifications in accordance with the invention, it will be appreciated that the invention is not limited thereto, but encompasses all expedients and variants within the scope of the appended claims.

What is claimed is:

1. A method of making optical waveguide fibers having very low attenuation, comprising the steps of:

depositing a core soot material along the axis of a rotating target by directing a first stream of core soot material towards the rotating target to develop a first soot core having a predetermined length;

depositing one or more additional layers of core soot material over the first soot core using a second stream of core soot material positioned radially at an angle substantially perpendicular to the axis of rotation to develop a soot core cylinder having a substantially uniform diameter along its length;

depositing cladding soot material on the outer surface of the soot core cylinder with a radial stream of cladding soot material to provide a cladding layer coextensive with the soot core cylinder;

drying and sintering the product thus formed; and

drawing the dried and sintered product into optical waveguide fibers.

2. The method of claim 1, further comprising the steps of: flowing a gas and oxygen mixture about the stream of cladding soot material to provide a converging flame, wherein the cladding soot stream has substantially constant cross-section.

3. The method of claim 2, wherein the flow of gas and oxygen mixture is gradually increased during initial deposition of cladding soot material on the previously deposited core soot material to limit surface temperature until an initial cladding layer is built up on the soot core cylinder.

4. The method of claim 1, wherein the soot core cylinder comprises silica and germania; and the cladding soot comprises silica.

5. The method of claim 1, further comprising the step of sintering the soot core cylinder before deposition of the cladding soot material.

6. The method of claim 1 wherein the step of sintering of the cladding takes place in a fluorine containing environment to generate fluorosilicate impregnated cladding having a lower index of refraction than the soot core cylinder.

7. The method of claim 6, wherein the fluorine environment comprises an atmosphere of helium and sulfur hexafluoride at a temperature in the range of about 1000-1150°C, and wherein the cladding is zone sintered.

8. The method of claim 1, wherein the axis of the rotating target is positioned vertically.

9. The method of claim 1, wherein the axis of the rotating target is positioned horizontally.

10. The method of claim 1, wherein the soot core cylinder is pre-densified before each additional soot core layer is deposited.

11. The method of claim 1, wherein the position and flow of the soot stream is varied to control the refractive index profile.

12. The method of claim 1, wherein the step of depositing additional layers of core soot material over the first soot core is accomplished by simultaneously spraying a plurality of core soot streams to form additional soot core layers, and wherein the step of depositing cladding soot material is accomplished by simultaneously spraying a plurality of cladding soot streams to form additional cladding layers.

13. The method of claim 1 further comprising the step of exhausting core soot material that bypasses the deposition surface away from the region of core soot material deposition.

14. The method of claim 1 wherein the soot core cylinder has a predetermined density profile.

15. The method of claim 14 wherein the density is substantially uniform.

16. The method of claim 4 wherein the cladding soot comprises doped silica.

17. A method of making a preform for optical waveguide fibers having attenuation of less than 1 dB/km, comprising the steps of:

depositing a core soot material along the axis of a rotating target by directing a first stream of core soot material towards the rotating target to develop a first soot core having a predetermined length and density;

depositing one or more additional layers of core soot material over the first soot core using a second stream of core soot material positioned radially at an angle substantially perpendicular to the axis of rotation.

18. The method of claim 17, wherein the step of depositing said one or more additional layers of soot core material is performed by reciprocating the second stream along the length of the first soot core to develop a substantially uniform density soot core cylinder having a substantially uniform diameter along its length.

19. The method of claim 18, wherein the first soot core and the soot core cylinder comprise silica and germania.

20. The method of claim 18, wherein the soot core cylinder is pre-densified with a plurality of end burners before each additional soot core layer is deposited.

21. The method of claim 17, wherein the axis of the rotating target is positioned vertically.

22. The method of claim 17, wherein the axis of the rotating target is positioned horizontally.

23. The method of claim 17, wherein the position and flow of the core soot streams are varied to control the refractive index profile.

24. The method of claim 23 wherein the refractive index profile is selected from the group consisting of a step-index profile, a semi-parabolic profile or a triangular refractive profile.

25. The method of claim 17, wherein the step of depositing one or more additional layers of core soot material is accomplished by simultaneously spraying a plurality of core soot streams to form additional soot core layers.

26. The method of claim 17 wherein the first soot core has a predetermined density profile.

27. The method of claim 26 wherein the density profile is substantially uniform.

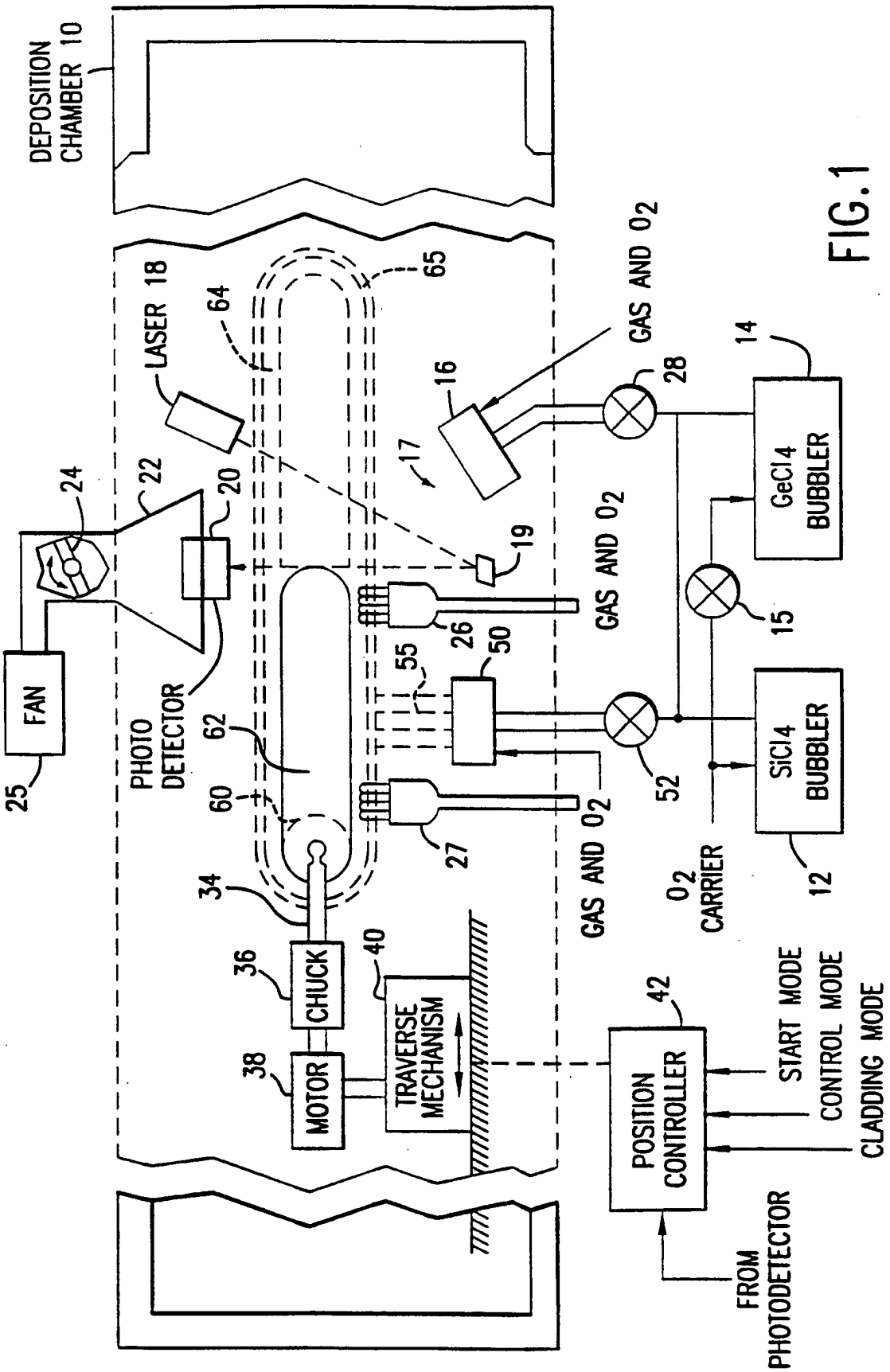

DEPOSITION CHAMBER 10
LASER 18
64
65
16
17
GAS AND O_2
28
14
GeCl4 BUBBLER
24
22
20
19
FAN
25
PHOTO DETECTOR
62
60
26
50
55
15
52
SiCl4 BUBBLER
12
27
34
O_2 CARRIER
36
CHUCK
40
38
MOTOR
TRAVERSE MECHANISM
42
POSITION CONTROLLER
START MODE
CONTROL MODE
CLADDING MODE
FROM PHOTODETECTOR

FIG. 1

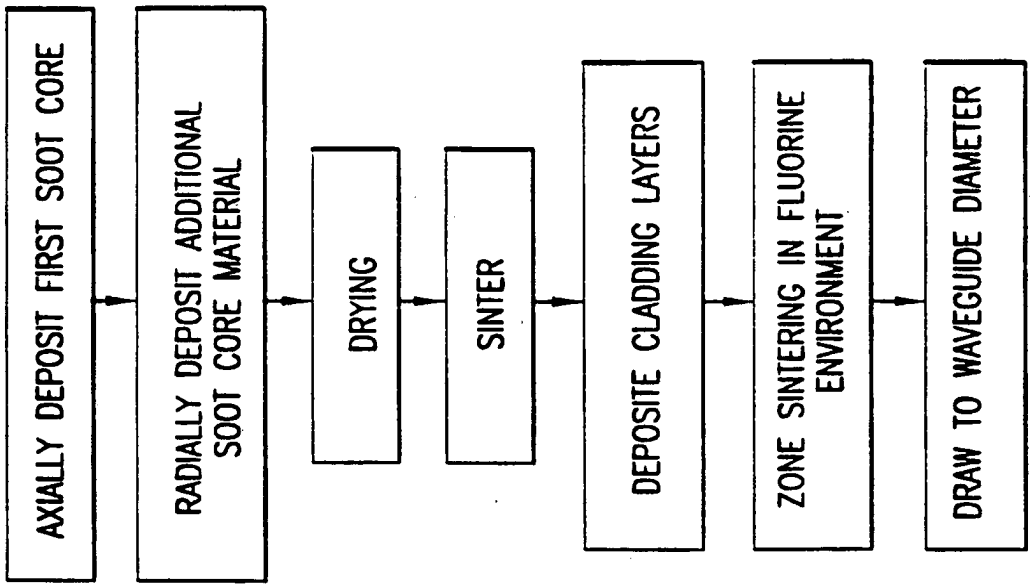

AXIALLY DEPOSIT FIRST SOOT CORE
RADIALLY DEPOSIT ADDITIONAL SOOT CORE MATERIAL
DRYING
SINTER
DEPOSITE CLADDING LAYERS
ZONE SINTERING IN FLUORINE ENVIRONMENT
DRAW TO WAVEGUIDE DIAMETER

FIG.3

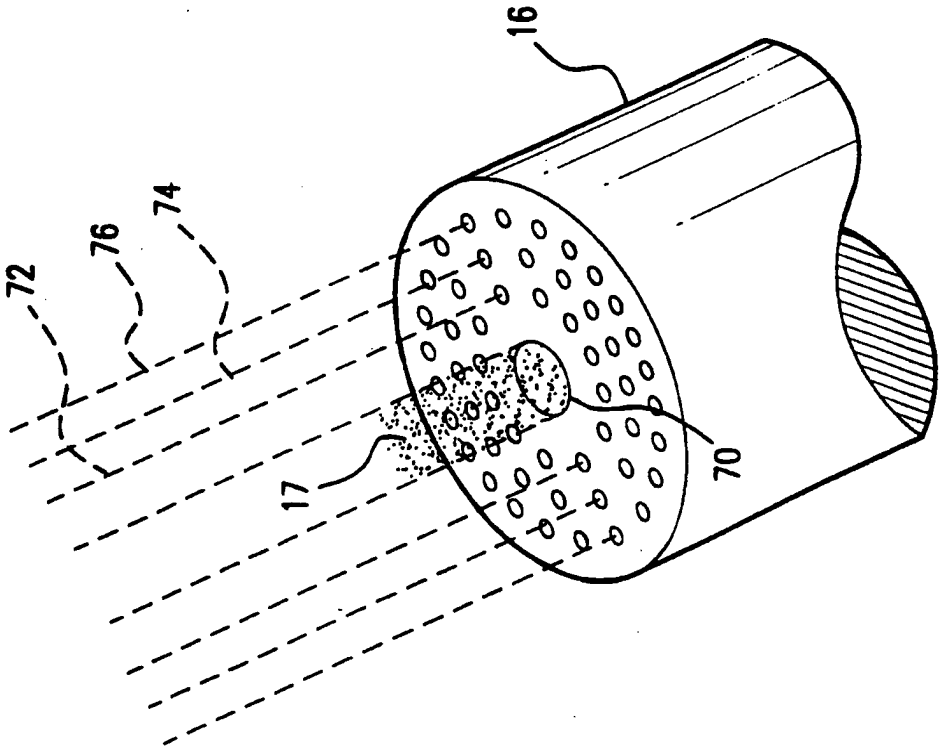

16
72
76
74
17
70

FIG.2

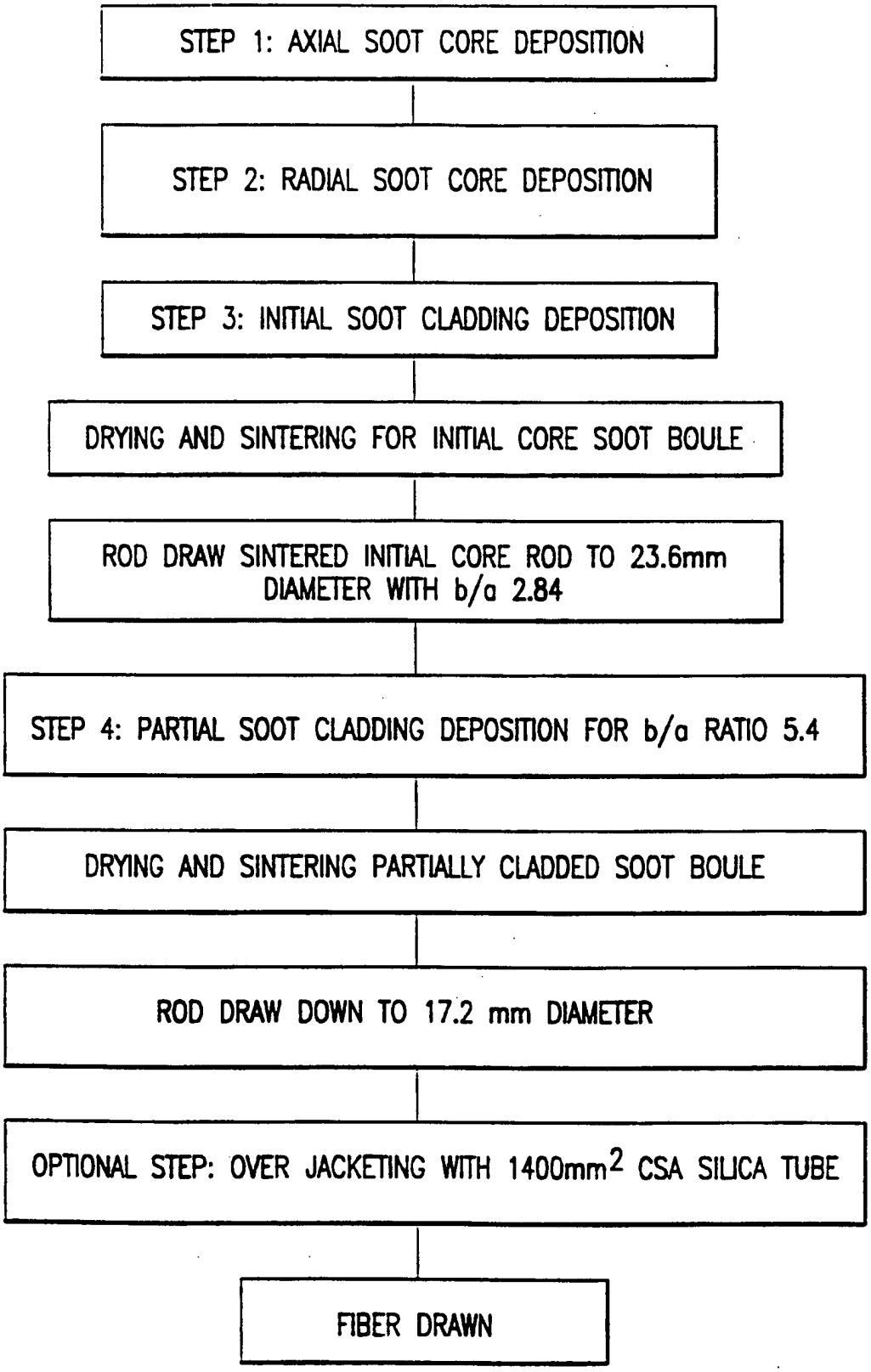

STEP 1: AXIAL SOOT CORE DEPOSITION
STEP 2: RADIAL SOOT CORE DEPOSITION
STEP 3: INITIAL SOOT CLADDING DEPOSITION
DRYING AND SINTERING FOR INITIAL CORE SOOT BOULE
ROD DRAW SINTERED INITIAL CORE ROD TO 23.6mm DIAMETER WITH b/a 2.84
STEP 4: PARTIAL SOOT CLADDING DEPOSITION FOR b/a RATIO 5.4
DRYING AND SINTERING PARTIALLY CLADDED SOOT BOULE
ROD DRAW DOWN TO 17.2 mm DIAMETER
OPTIONAL STEP: OVER JACKETING WITH 1400mm2 CSA SILICA TUBE
FIBER DRAWN

FIG.4

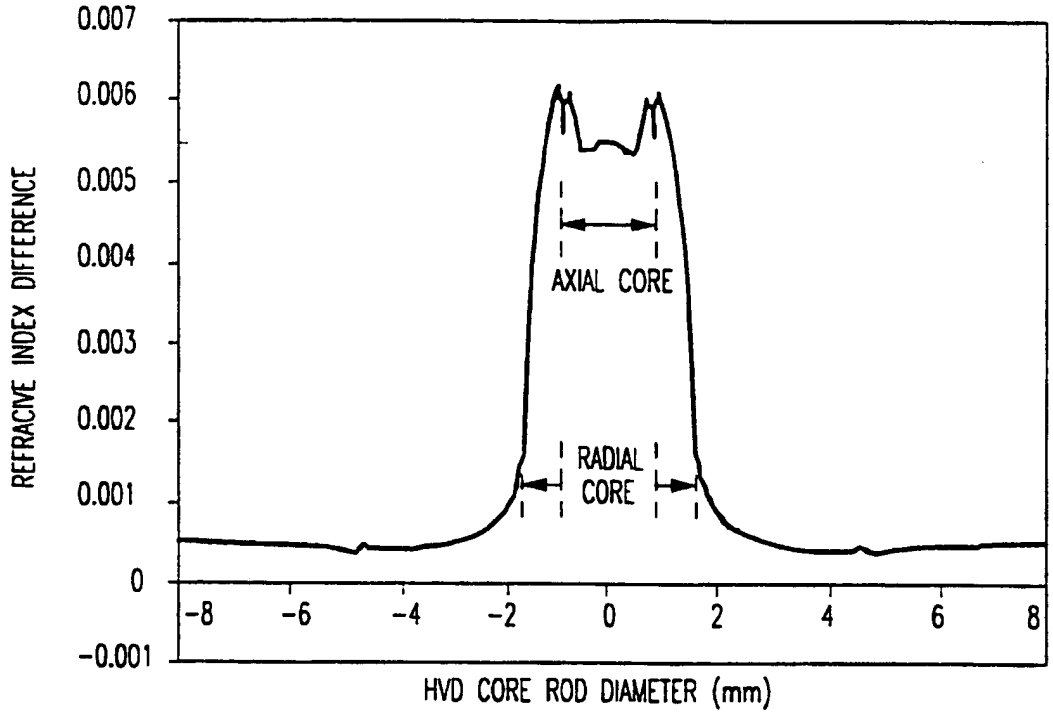

0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
REFRACIVE INDEX DIFFERENCE
AXIAL CORE
RADIAL CORE
-8
-6
-4
-2
0
2
4
6
8
HVD CORE ROD DIAMETER (mm)

FIG.5

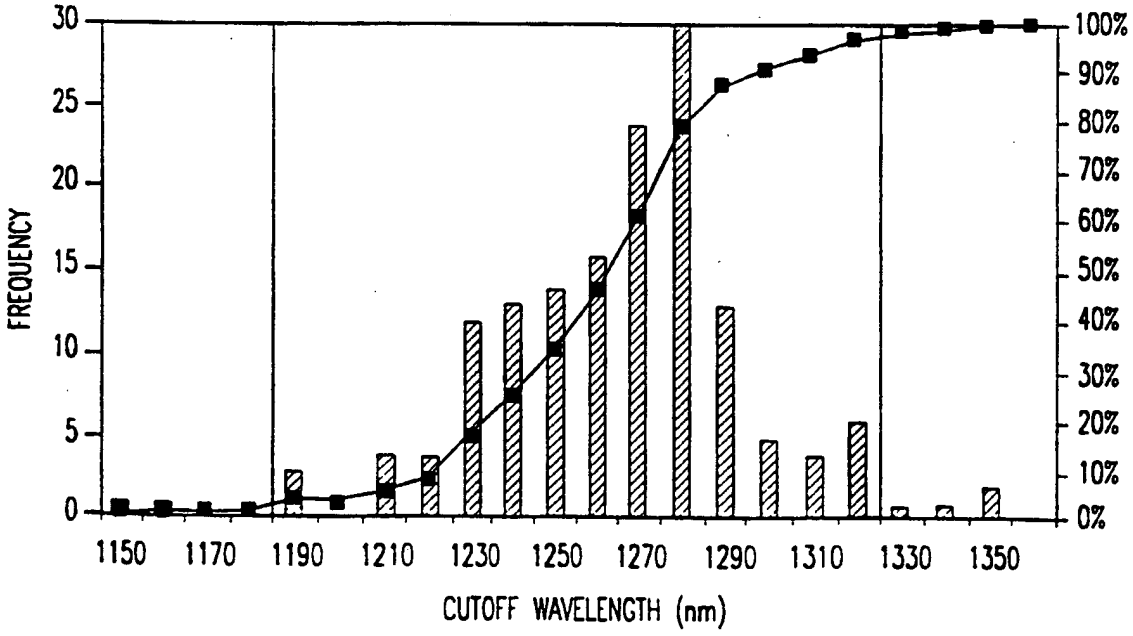

30
25
20
15
10
5
0
FREQUENCY
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1150
1170
1190
1210
1230
1250
1270
1290
1310
1330
1350
CUTOFF WAVELENGTH (nm)

FIG.6

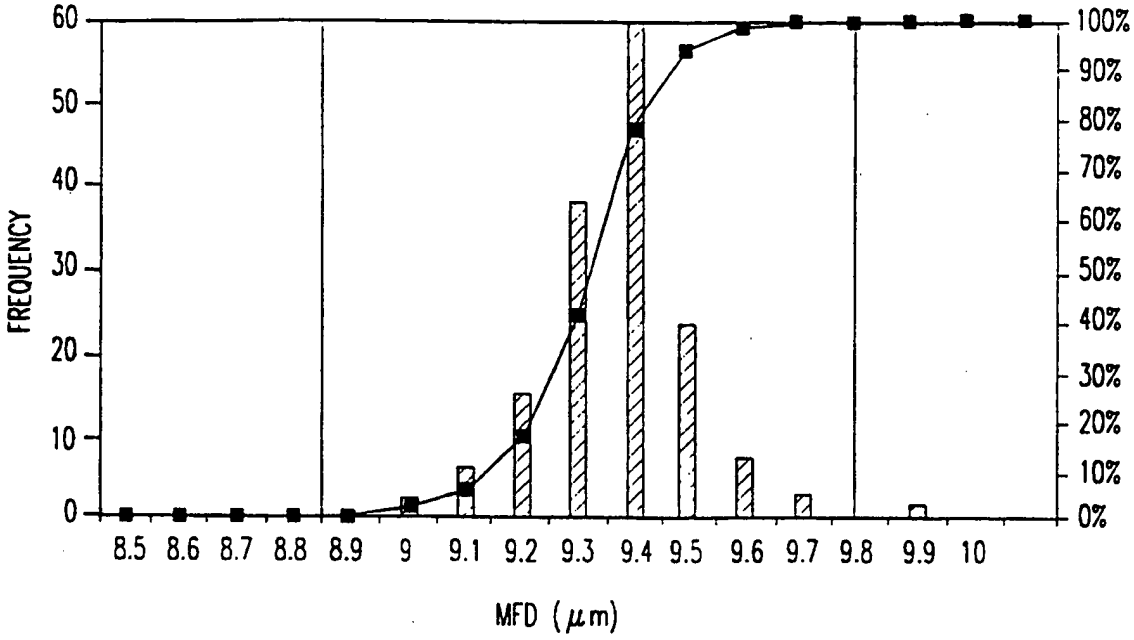

FREQUENCY
60
50
40
30
20
10
0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
8.5 8.6 8.7 8.8 8.9 9 9.1 9.2 9.3 9.4 9.5 9.6 9.7 9.8 9.9 10
MFD (μm)

FIG.7

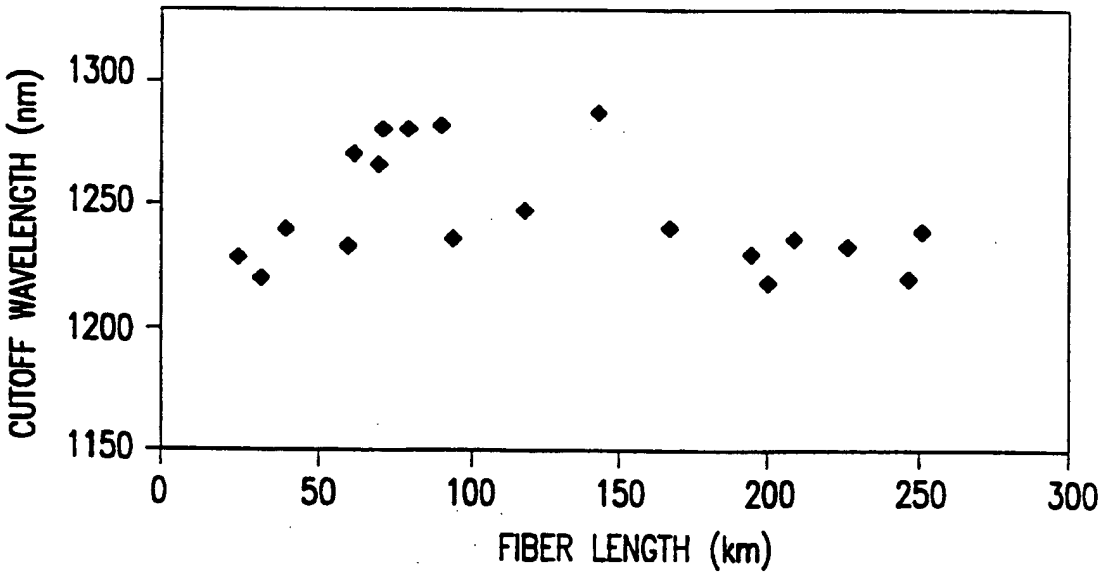

CUTOFF WAVELENGTH (nm)
1300
1250
1200
1150
0 50 100 150 200 250 300
FIBER LENGTH (km)

FIG.8

TABLE 4: A SUMMARY OF SSS HVD SINGLE-MODE FIBERS' PERFORMANCE			
	DESIGN TARGET	DESIGN OUTPUT (AVERAGE)	% FIBER WITHIN TARGETS
CUTOFF λc (nm)	1255 +/- 65 nm	1260	92%
MFD@1.3 μm	9.3+/-0.5 μm @1310nm	9.35	99.35%
MFD@1.55 μm	10.5+/-1.0 mm @1550nm	10.7	100%
0-DISP. λ (nm)	1301.5 TO 1321.5 nm	1316	98.25%
DISP. SLOPE	=<0.092 (ps/nm^2-km)	0.0858	100%
Att @1310nm	=<0.4 dB/km	0.33 (PEAK)	97.96%
Att @1380nm	=<2.0dB/km	0.5 (PEAK)	100%
Att. @1550nm	=<0.3dB/km	0.185 (PEAK)	98.64%
CORE NC(%)	=<5%	1.0% (PEAK)	97.14%
CLAD NC(%)	=<2%	0.7% (PEAK)	99.29%
CORE/CLAD OFFSET	=<1 μm	0.3 (PEAK)	93.57%

FIG.9A

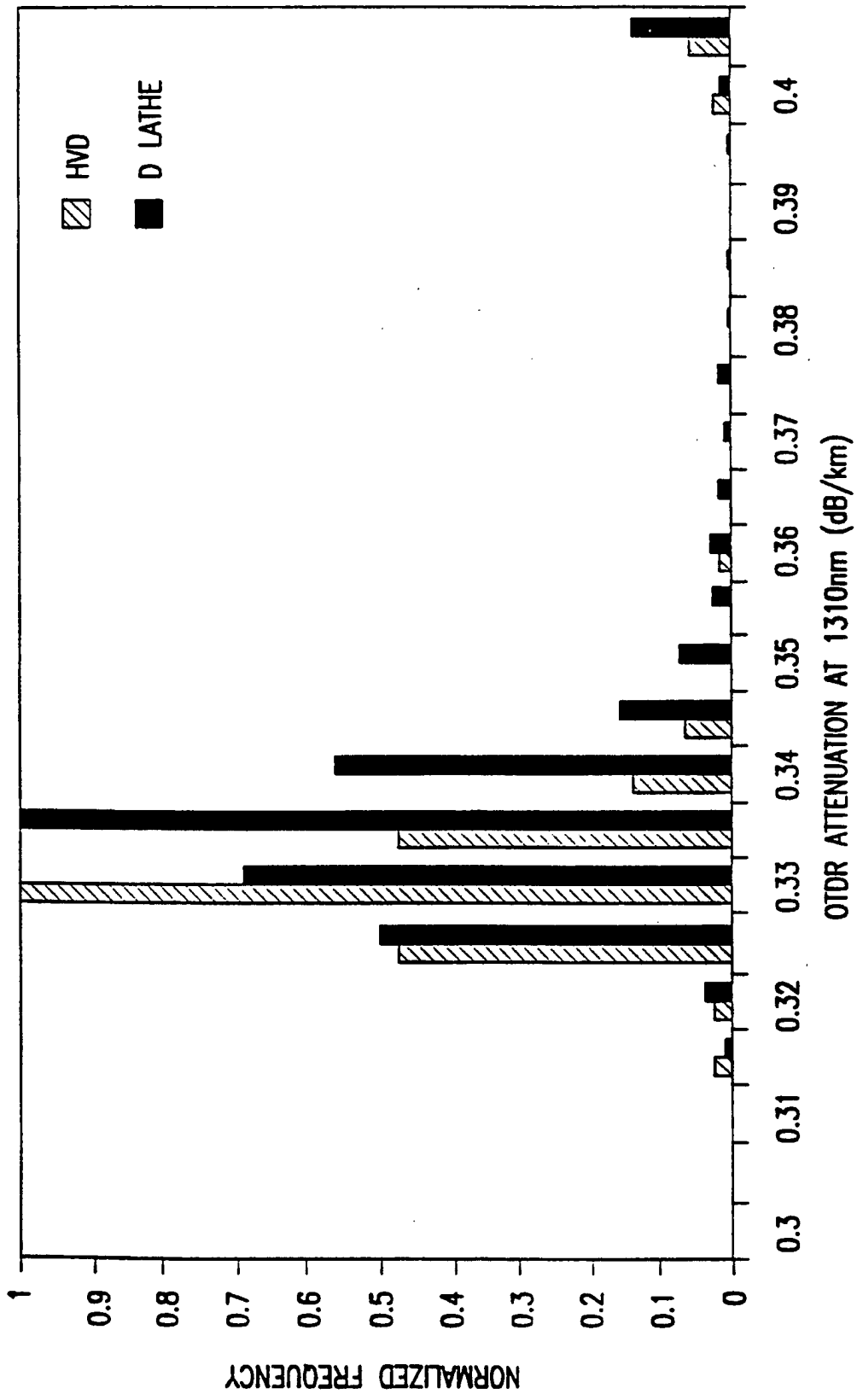

HVD
D LATHE
NORMALIZED FREQUENCY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.3
0.31
0.32
0.33
0.34
0.35
0.36
0.37
0.38
0.39
0.4
OTDR ATTENUATION AT 1310nm (dB/km)

FIG.9B

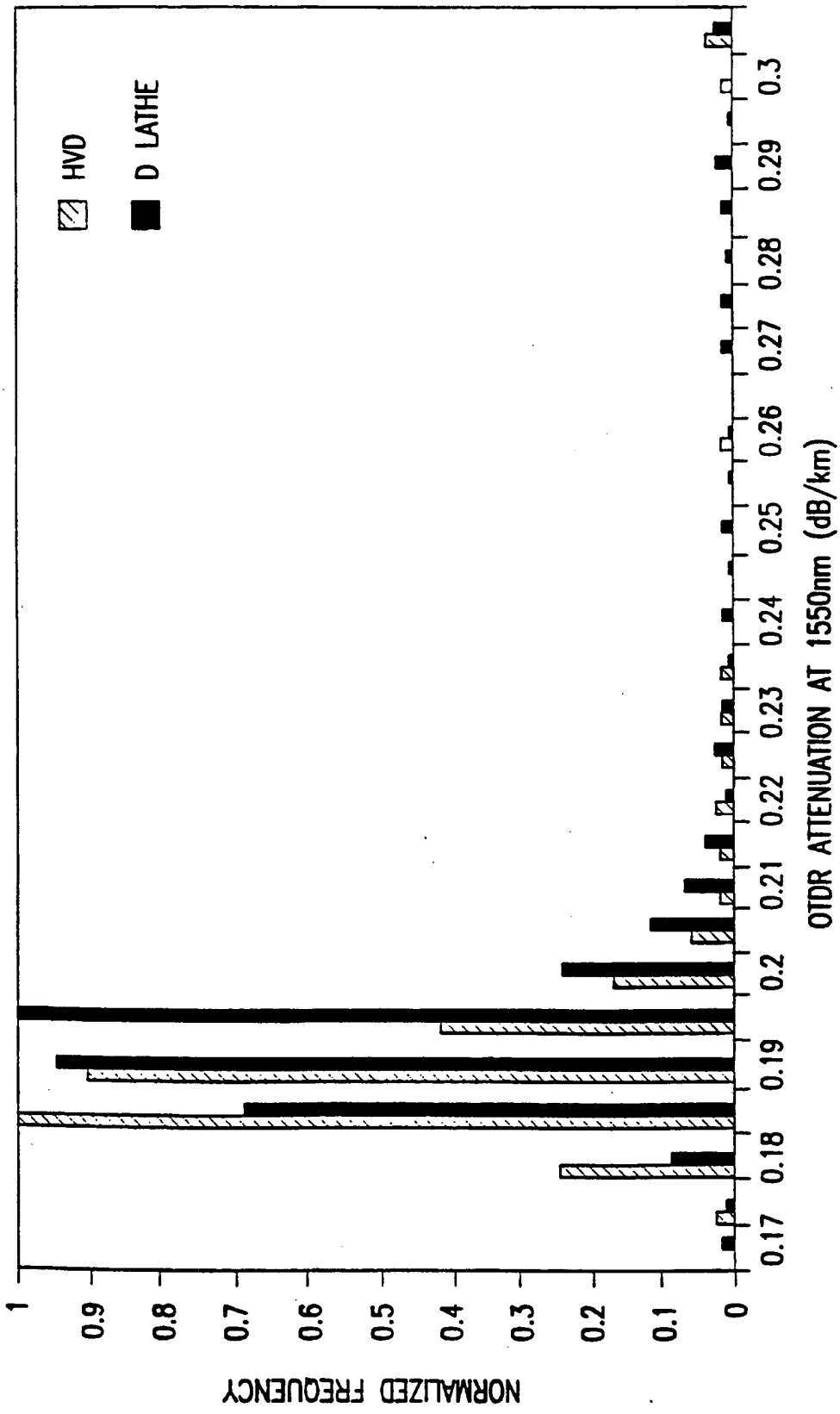

HVD
D LATHE
NORMALIZED FREQUENCY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.17
0.18
0.19
0.2
0.21
0.22
0.23
0.24
0.25
0.26
0.27
0.28
0.29
0.3
OTDR ATTENUATION AT 1550nm (dB/km)

FIG.10

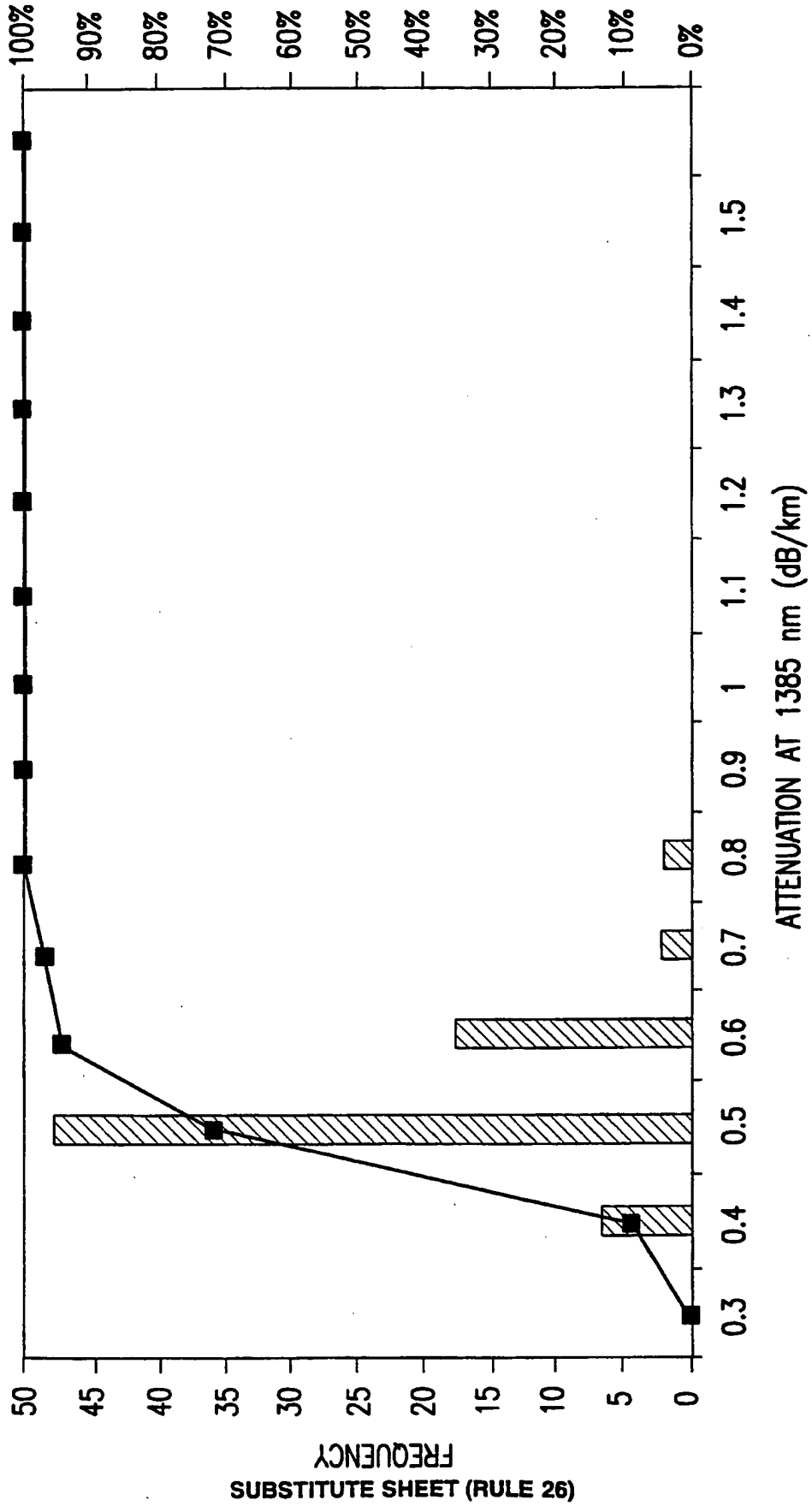

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
ATTENUATION AT 1385 nm (dB/km)
0
5
10
15
20
25
30
35
40
45
50
FREQUENCY

FIG.11

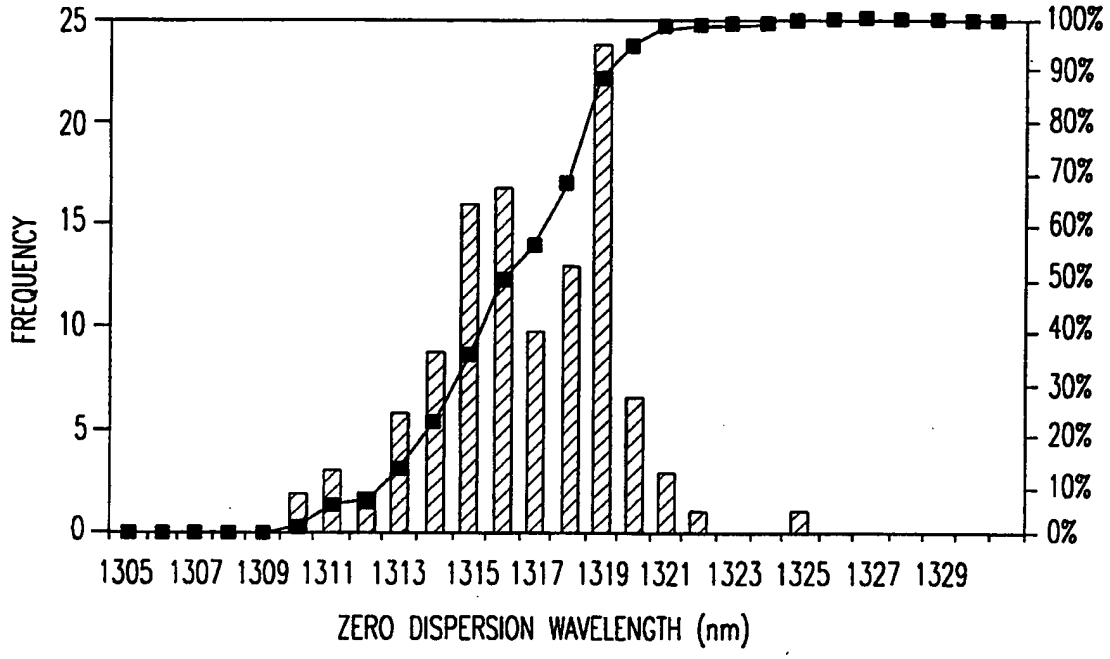

25
20
15
10
5
0
FREQUENCY
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1305 1307 1309 1311 1313 1315 1317 1319 1321 1323 1325 1327 1329
ZERO DISPERSION WAVELENGTH (nm)

FIG.12

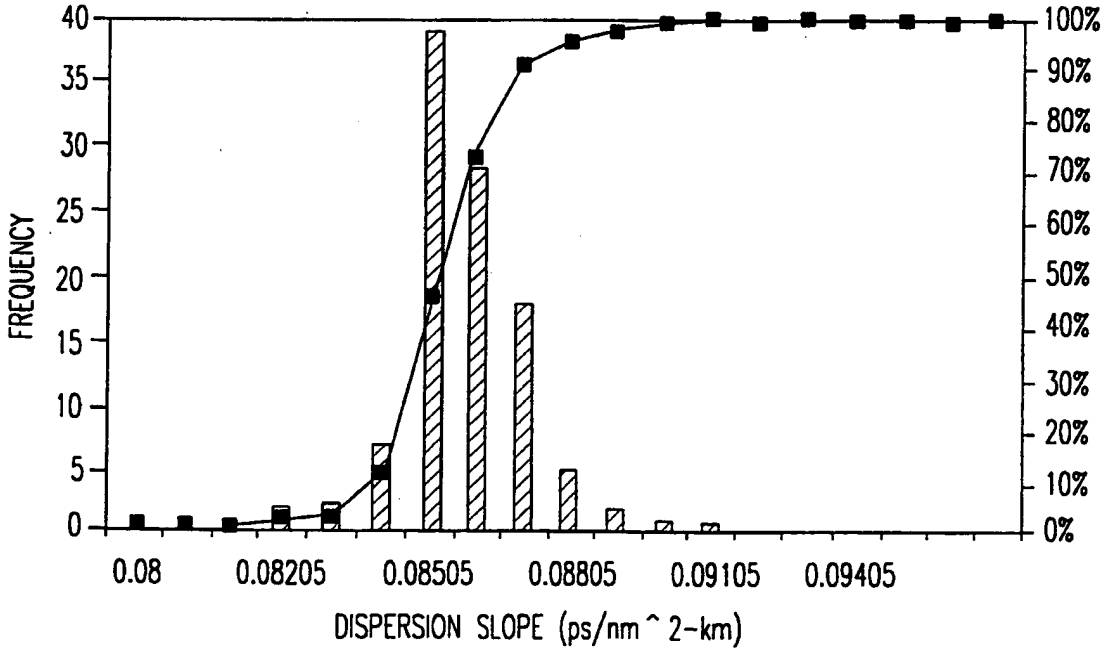

40
35
30
25
20
15
10
5
0
FREQUENCY
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.08
0.08205
0.08505
0.08805
0.09105
0.09405
DISPERSION SLOPE (ps/nm ^ 2-km)

FIG.13

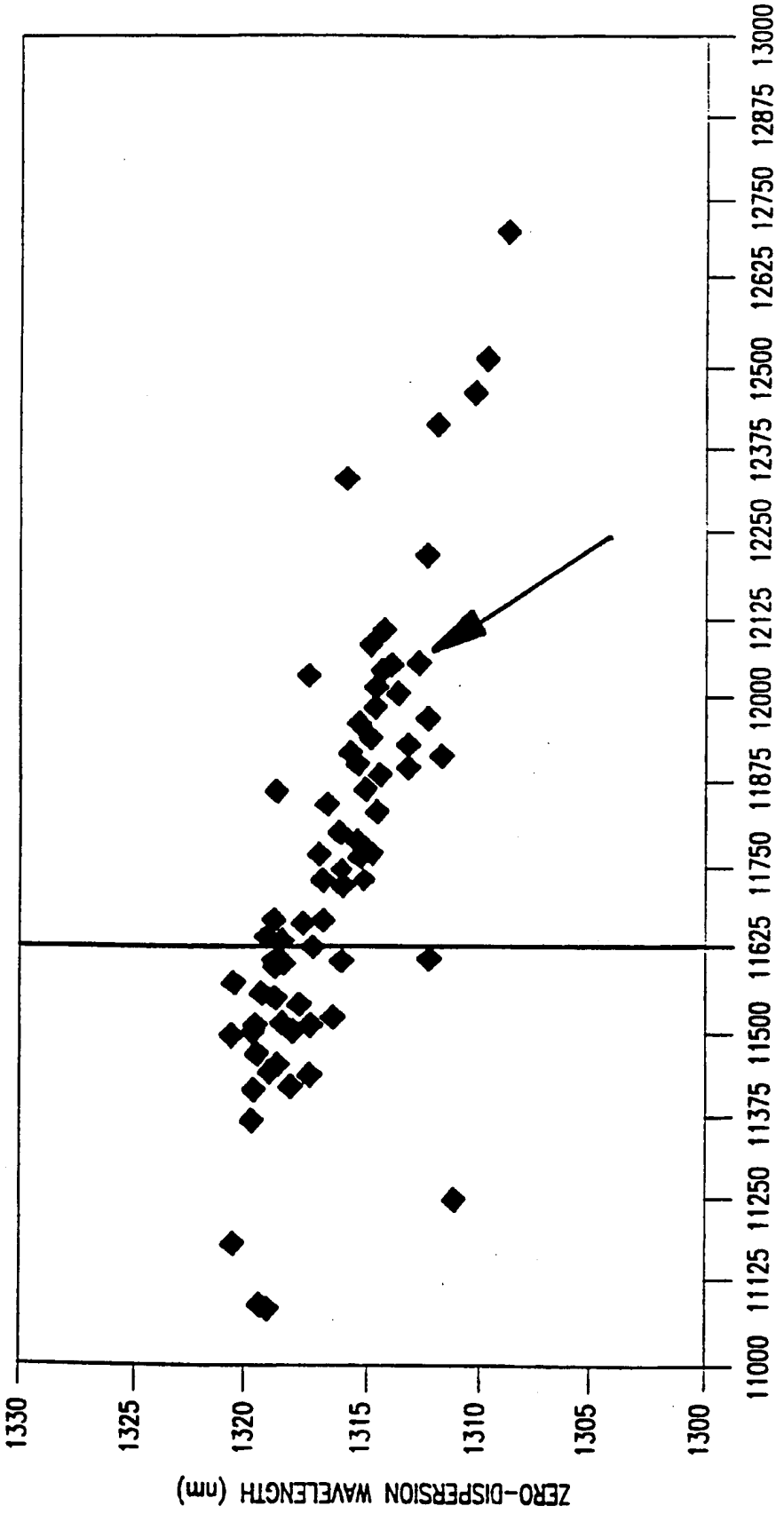

ZERO-DISPERSION WAVELENGTH (nm)
1330
1325
1320
1315
1310
1305
1300
MFD* λ c(μ m*nm)
11000
11125
11250
11375
11500
11625
11750
11875
12000
12125
12250
12375
12500
12625
12750
12875
13000

FIG.14

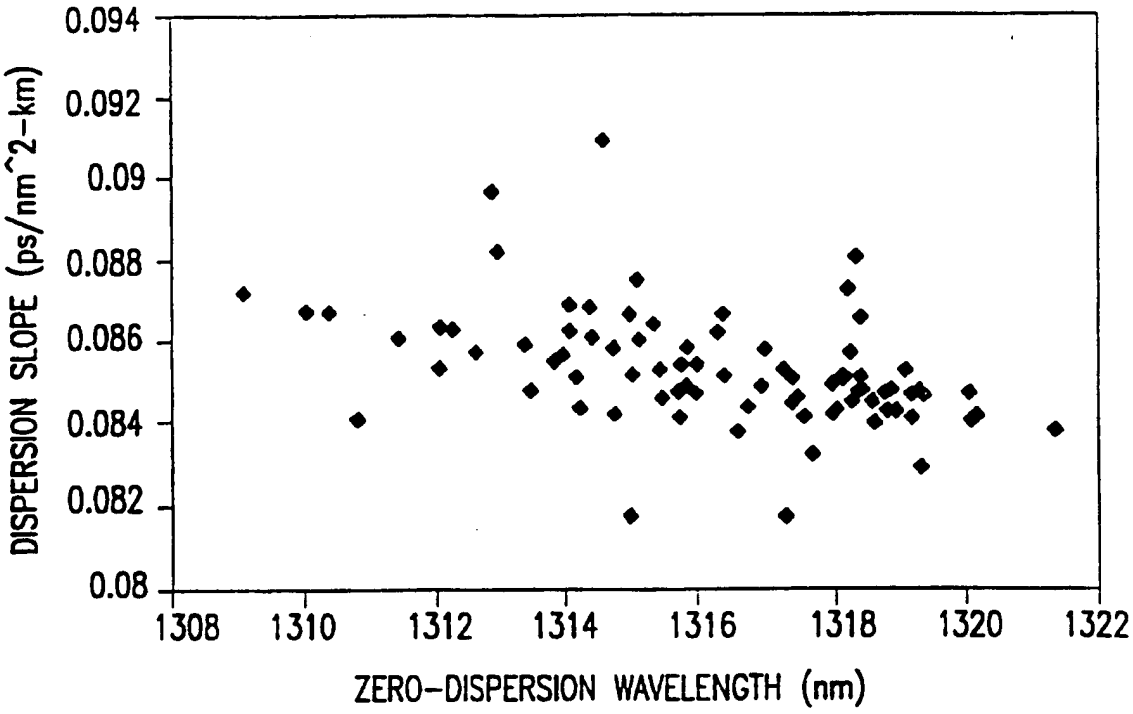

0.094
0.092
0.09
0.088
0.086
0.084
0.082
0.08
DISPERSION SLOPE (ps/nm^2-km)
1308
1310
1312
1314
1316
1318
1320
1322
ZERO-DISPERSION WAVELENGTH (nm)

FIG.15

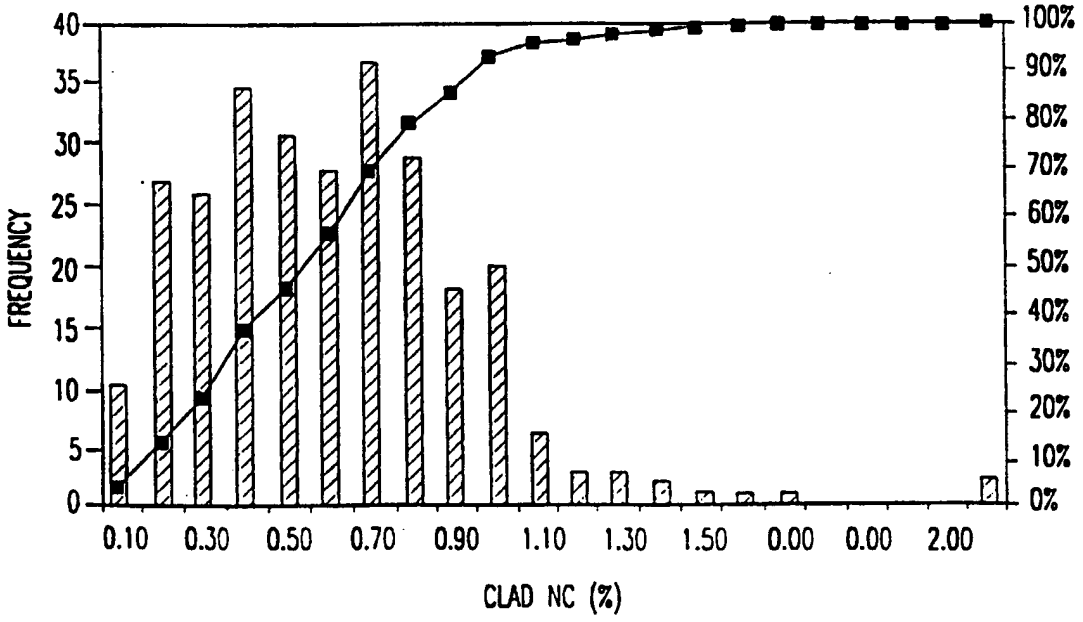

40
35
30
25
20
15
10
5
0
FREQUENCY
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.10
0.30
0.50
0.70
0.90
1.10
1.30
1.50
0.00
0.00
2.00
CLAD NC (%)

FIG.16

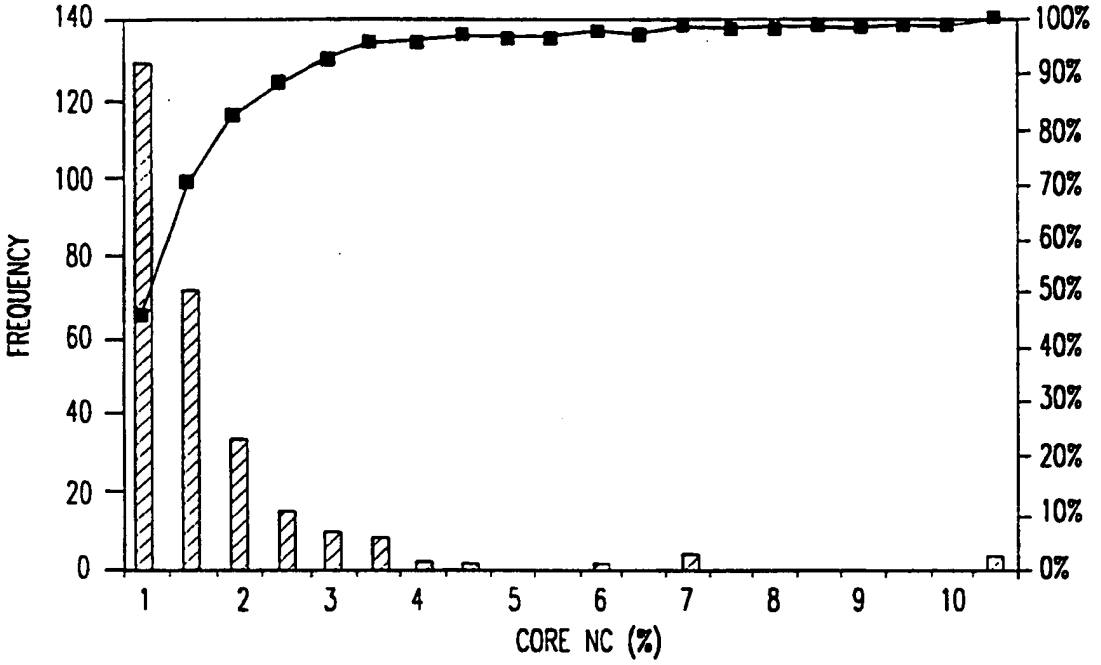

FREQUENCY
140
120
100
80
60
40
20
0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1
2
3
4
5
6
7
8
9
10
CORE NC (%)

FIG.17

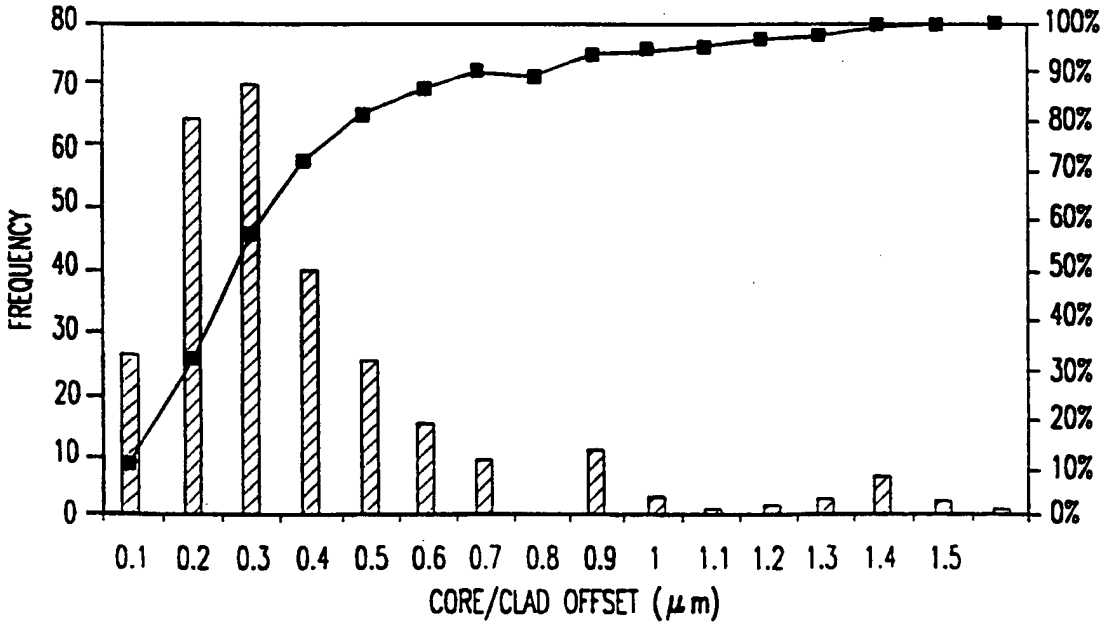

FREQUENCY
80
70
60
50
40
30
20
10
0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
CORE/CLAD OFFSET (μm)

FIG.18

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/27418

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :C03B 37/014, 37/018
US CL :65/397, 398, 422, 427

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 65/397, 398, 422, 427

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 3,823,995 A (CARPENTER) 16 July 1974, see entire document, especially figure 2.	1-27
Y	US 4,298,365 A (BAILEY et al) 03 November 1981, entire document especially figure 2.	1-27

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search	Date of mailing of the international search report
17 MARCH 1999	12 APR 1999

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	JOHN HOFFMANN
Facsimile No. (703) 305-3230	Telephone No. (703) 308-0661

Form PCT/ISA/210 (second sheet)(July 1992)*